A new era in super-accurate omated flight is dawning. Tiny, highly reliable airborne computers of the new generation make it possible for every aircraft and missile to carry unlimited, low-cost computational power. The possibilities for improving navigational accuracy and weapon flexibility are so vast that it is certain that . . .

As Computers Shrink, Their Uses Grow

By J. S. Butz, Jr.

TECHNICAL EDITOR, AIR FORCE/SPACE DIGEST

HISTORIANS tell us to step back and take the long view if we hope to see the true course of human events. They say that too close a look, too much concentration on specific problems, can obscure the matters of greatest importance.

Historians can afford this luxury. Few reporters, facing daily deadlines, can. A case in point is much of today's reporting on the technological revolution. Because reporters often concentrate on a few problem areas, the impression is left that technical progress is faltering, that it creates more problems than it solves, that the benefits are not commensurate with the cost. Actually, the technological revolution has reached avalanche proportions and is certain to hit a weary world soon with the strongest technical shocks humanity has yet experienced.

No better example of this short view exists today than in the airborne-computer field. Public reports on major computer programs have concentrated on cost overruns, criticisms of management, and technical problems. All of these have been substantial and worthy of notice.

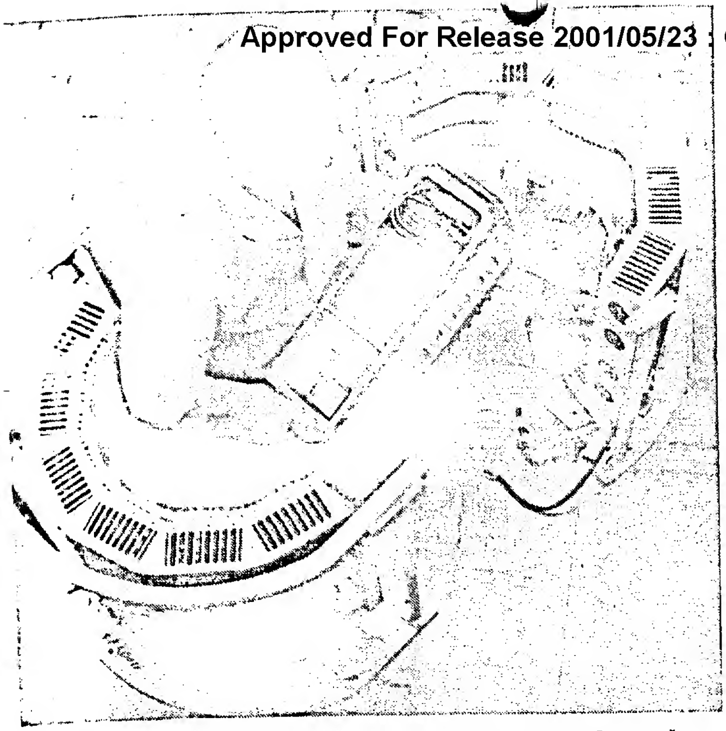
But the press understandably has failed to convey the most important news. Despite all the problems, technical progress is moving at a fantastic speed. A bona fide revolution has taken place in the past decade. Airborne-computer systems of 1960 are completely outclassed by those of 1969. What's more, there is no end in sight and more important advances are forecast for the 1970s.

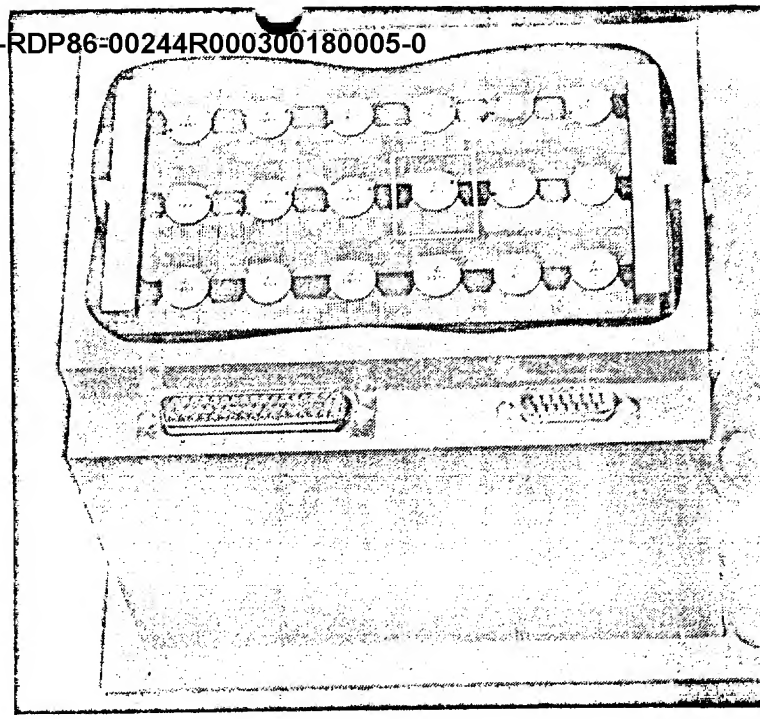
Some predictions are so glowing they are difficult to accept, but they are supported by the record. According to one prognosticator, Glen M. Harold of Control Data Corp., by 1974 an up-to-date airborne computer, equal in performance to the Minuteman I unit *(see page 29)*, will be little larger than a bump in a wire. Instead of costing nearly $500,000, as the Minuteman I system did, the price of the 1974 version would be around $10,000. Just as important, reliability would be improved by one hundred times or better.

Key yardsticks for measuring progress are shown in the tables on page 30. The values beyond 1968 are based on Mr. Harold's predicted timetable. Other experts agree that this type of performance is achievable, but some believe that the "bump-in-the-wire" computer will not become possible until a few years later than 1974.

From the military standpoint it is impossible to underestimate the significance of such an improvement in technology. Computers are the key to giving missiles and aircraft greater operational flexibility and accuracy in attacking targets through any kind of weather and all types of enemy defenses.

As computers grow smaller, cheaper, and more reli-





Four generations of airborne computers are shown here. The oldest two (above, left) are military. The technician is kneeling between the halves of the Minuteman I computer rack. He is holding the computer for the Minuteman II. Current technology is represented by Autonetics' company-developed D200 (above right), which is comparable in performance to the Minuteman II model and sells at less than $25,000 on the commercial market. The white box around one of the D200 chips shows the approximate size of the next generation of computers, expected in the mid-1970s.

able, they can be ganged together to give all flying vehicles almost unlimited computational power. Coupled through elaborate logic circuits to a complete array of modern sensors, such high-capacity computers can give a warhead almost unlimited potential for recognizing and evading defenses while still achieving unparalleled accuracy in weapon delivery.

Strategic armaments naturally have been the first affected by the airborne-computer revolution. This new technology is the primary reason behind the continuous obsolescence of US long-range missiles, which have had the shortest useful life of any major weapon system in history. Three generations were deployed in a period of ten years and a fourth is under development.

The first ICBM, the liquid-fueled Atlas, has been completely retired from the inventory. Only a few storable liquid-fueled Titans still are in service. Minuteman I, the first intercontinental missile with solid-fuel motors, replaced the liquid-rocket models, and also brought a more powerful and flexible guidance system into the inventory. It has been replaced to a great degree by Minuteman II, which has a guidance system of far greater accuracy. Former Secretary of Defense Robert S. McNamara described Minuteman II as a bigger improvement over Minuteman I than the B-52 was over the B-17. Now the Minuteman II guidance, which has been in service only four years, is thoroughly outdated by the Minuteman III system, which will be able to control several MIRV (Multiple Independently-targetable Reentry Vehicle) warheads. And MIRV technology is in its infancy.

Today, the airborne-computer revolution promises to furnish answers to many military problems beyond the one of keeping strategic weapons up to date. Computer size and cost are shrinking to the point that computers soon can be used in very large numbers. It will be possible to guide small tactical missiles with extremely high accuracy and to provide them with elaborate maneuvering capability. Within a decade it will be possible to build a complete new stable of air-to-air, air-to-ground, ground-to-air, and ground-to-ground missiles that will thoroughly outclass today's weapons.

The day also is in sight when rocket-assisted artillery shells, equipped with low-cost terminal guidance, can achieve pinpoint accuracy at ranges beyond 100 miles. Such a guidance system would couple a relatively simple fifth-generation *(see table, page 30)*, bump-in-the-wire computer with one of several possible sensors. Some industry experts believe the complete system could turn out to be cheaper than the radio proximity fuzes of World War II.

A host of other changes will become mandatory when low-cost, unlimited computational power becomes available to the military. The most complex operations, from the surveillance of wide areas to the control of battles, can be automated to an extent not even dreamed possible ten years ago. Networks of hundreds, even thousands, of sensors can be monitored continuously. Every small unit, possibly every vehicle, can have a computer. [illegible] will be possible in very large volume, and the logic capacity of the system will

(Continued on following page)

be so formidable that many of the laboriously prepared orders and reports now required to keep military units functioning will be handled automatically.

An example would be a decision by a high-level commander to engage a specific target. He would punch this decision into the computer, and fire orders would appear instantly at the weapons and in the vehicles to which the task was assigned. It is conceivable that these fire orders could even include specific azimuth and range to target for each weapon.

Such a picture of a computerized battlefield can only be seen by stepping back and taking the long view, by using the actual improvements in technology over the past decade to predict what should be possible in the next ten to fifteen years.

Looking too closely at specific programs brings one into range of a cacophony of arguments within the electronics industry about what should be done next, and charges and countercharges within government and industry about the success or failure of past and present programs. The arguments go down to such basic matters as definition of technical terms. There is very little agreement about anything in the electronics business. It has been racked by constant change for more than a decade, and the prospect is for greater change in the years ahead.

However, by accepting a broad definition of terms and a generous allowance for performance estimates, it is possible to break down the computer revolution into five basic generations of machines. A table of the generations is presented on this page; it is derived from material from Mr. Harold, and it checks well with material from other experts.

The mechanical computer, or zero generation, reached its zenith during World War II in Dr. Vannevar Bush's differential analyzer for controlling antiaircraft gunfire.

First-generation electronic-calculation devices were built around 1950, using vacuum tubes. Shortly after, the electronics industry experienced its first major technical revolution in the birth of the transistor and solid-state active devices. By 1956 these devices were being used in computers.

Minuteman I was one of the first major programs to depend on a transistorized airborne computer. Its performance far exceeded the most optimistic estimates of either the Air Force or the contractor, Autonetics Division of North American Rockwell. Mean time between failures on the complete guidance and control system was about double the contract requirements, as shown on page 32. Total cost of the guidance and control system, including R&D as well as production, was within 2.5 percent of the target, even though large numbers of changes were specified by the government and a very rapid schedule was maintained. The initial contract was awarded late in 1958, and the first Minuteman I was operational four years later, in the last quarter of 1962.

The unexpected durability of the guidance system paid off handsomely for USAF. This system had to operate continuously in the silo, with gyros running, so that the missile would be ready for instant flight. Since each missile could operate much longer than expected between maintenance periods, the total number needed to meet the launch-ready requirements was reduced. The computer/guidance system also proved to have a better in-flight reliability and weapon-delivery accuracy than originally specified, which further reduced the number of missiles required to perform the Air Force mission. The cost avoidance in procuring fewer missiles was estimated by the Department of Defense at $1 billion.

Success with Minuteman I did not bring stability however, because another revolution, as destabilizing as the advent of the transistor, hit the electronics industry. This was the practical development of microelectronic devices, in which several semiconductor elements could be deposited on a tiny chip of silicon.

As late as 1959, these integrated-circuit devices were [illegible]tists, and they were still in the laboratory stage. Few industry experts believed that they would reach the engineering stage in less than

GENERATIONS OF COMPUTERS

Introduced	Generation	Technology	Application Examples
—	"Zero"	Mechanical	Gear-driven calculators
1950	First	Vacuum Tubes	Early computers
1956	Second	Transistors	Minuteman I
1962	Third	Integrated Semiconductor Circuits (ISC) 4 logic gates per chip	Minuteman II and III
1966	Third-and-a-Half	Medium-Scale Integration of Microcircuits (MSC) 100 logic gates per chip	
1968	Fourth	Large-Scale Integration (LSI) 1,000 logic gates per chip	Autonetics D200 Hayakawa Calculator
1974	Fifth	10,000 logic gates per chip	

COMPUTER TRENDS SUMMARY

Feature	1962	1967	1972
Size	2 cubic feet	0.7 cubic feet	0.1 cubic feet
Weight	100 pounds	35 pounds	8 pounds
Power	250 watts	80 watts	25 watts
Speed (in millionths of a second)	200 microseconds	30 microseconds	5 microseconds
Cost	$160,000	$30,000	$8,000
Airborne Mean Time Between Failure (MTBF)	330 hours	10,000 hours	150,000 hours

The scorching pace of computer technology is illustrated in these tables. The military services paid most of the R&D costs for the first three generations and then did not press to develop fourth-generation systems. That initiative was assumed by industry. Various fourth-generation devices are available commercially, and the market is expanding rapidly. The Electronic Industries Association estimates the market for fo[illegible] equipment will reach $500 million by 1973. The lower table, representing sixty aerospace computers, contains data for the "average" system.

decade. But the was extremely rapid. By 1961, it was widely believed that the only way to increase reliability and computational capacity for airborne computers was by using integrated circuits and that the way was now open to do so. This conviction about the readiness of the technology resulted in the beginning of the Minuteman II project in mid-1962, before Minuteman I even became operational.

The Minuteman II program looked pretty good. It could possibly be given as high a rating as the Minuteman I efforts even though it suffered some major overruns. High marks must be awarded because the Minuteman II guidance and control represented far more than a product improvement. It was completely new, the first major military system to use microelectronics. In terms of equivalent electronic parts of the vacuum-tube-era variety, the Minuteman II guidance and control system was the equal of 64,033, while the Minuteman I system was the equal of 17,444. The Minuteman II computer was rated as two and a half times more complex than its predecessor.

All did not go well. When Minuteman II became operational late in 1965, its guidance set displayed an alarmingly low reliability rate in-silo, as shown on page 32. Its reliability had been set by contract to be equal to that demonstrated by the Minuteman I guidance, but it fell far short of the goal and its useful life was seventy-five percent below predictions. To complicate matters further, Autonetics was not able to solve its manufacturing problems with the tiny microcircuits very quickly, and there was delay in setting up a depot repair system.

Militarily, the situation became serious in 1966 and 1967, as the Air Force launch-ready requirements were not met and a large percentage of the Minuteman II force was out of service because of a lack of guidance sets.

Two major corrective actions were taken. One was an increase in guidance-set production. The other was a large reliability-improvement program by Autonetics, called the Minuteman II Recovery Program. It was predicted within the government in 1966 and 1967 that this activity would add some $400 million to the cost of the guidance—for an overrun near sixty percent—making the total cost about $1.1 billion.

In abandoning the long view and moving closer to this problem, one runs into a thicket of conflicting reports. The Air Force and Autonetics reported that changes in the computer had brought it to a satisfactory state by 1969. Most of the guidance-set problems now are associated with the PIGA (Pendulous Integrating Gyroscopic Accelerometer), which is supplied through the Massachusetts Institute of Technology Instrumentation Laboratory. Warhead accuracy with Minuteman II also is better than specified.

Newspaper accounts have told a different story. One article last June, by Bernard D. Nossiter in the Washington *Post*, said, "A defense contractor who produced substandard 'brains' for the Minuteman II missile has received an estimated $400 million in additional orders for the same device." In July of this year, Patrick Sloyan, writing quoted a "strategic weapon adviser to Defense Secretary Melvin Laird" as saying, "I am seriously concerned about the reliability of Minuteman II. I have more confidence right now in Minuteman I than in Minuteman II."

Hayakawa Electric Company in Japan builds the desk-top calculator above, using three large-scale integrated (LSI) microelectronic circuits that it imports from Autonetics in the United States. Autonetics is supplying large numbers of these LSI chips under the terms of a $30 million contract.

Further confusion on Minuteman II costs has been generated by the congressional testimony of C. Merton Tyrell, a former Air Force management consultant. He contended last June that the total cost overrun on the missile, including all subsystems as well as guidance, had skyrocketed to almost $4 billion. Mr. Laird recently put the overrun at about $500 million when he reported the cost condition of all major programs to Congress.

The Washington *Post* has also carried stories by Mr. Nossiter which concluded that the electronic systems of the 1950s were more reliable and, therefore, more useful than those of the 1960s. No mention was made of the fact that the microminiaturized systems could handle tasks that were far beyond the capacity of the older equipment. And no mention was made of the fact that the integrated circuits now are realizing their reliability potential after a shaky start.

Back to the long view, another good measure for the speed and direction of computer technology is provided by the change in aircraft-navigation systems. In the mid-1950s there were no computer-controlled inertial-guidance systems aboard aircraft. Today, after signifi- [illegible] are in service aboard commercial jetliners as well as military aircraft. Most

(Continued on following page)

tional accuracy.

The next step is to improve this accuracy still further, to a few hundred feet, to satisfy bo[illegible]ng requirements. Industry's general approach to the problem is to use a high-capacity microminiaturized computer, which will use the inputs from a variety of sensors to constantly correct the error in the inertial system.

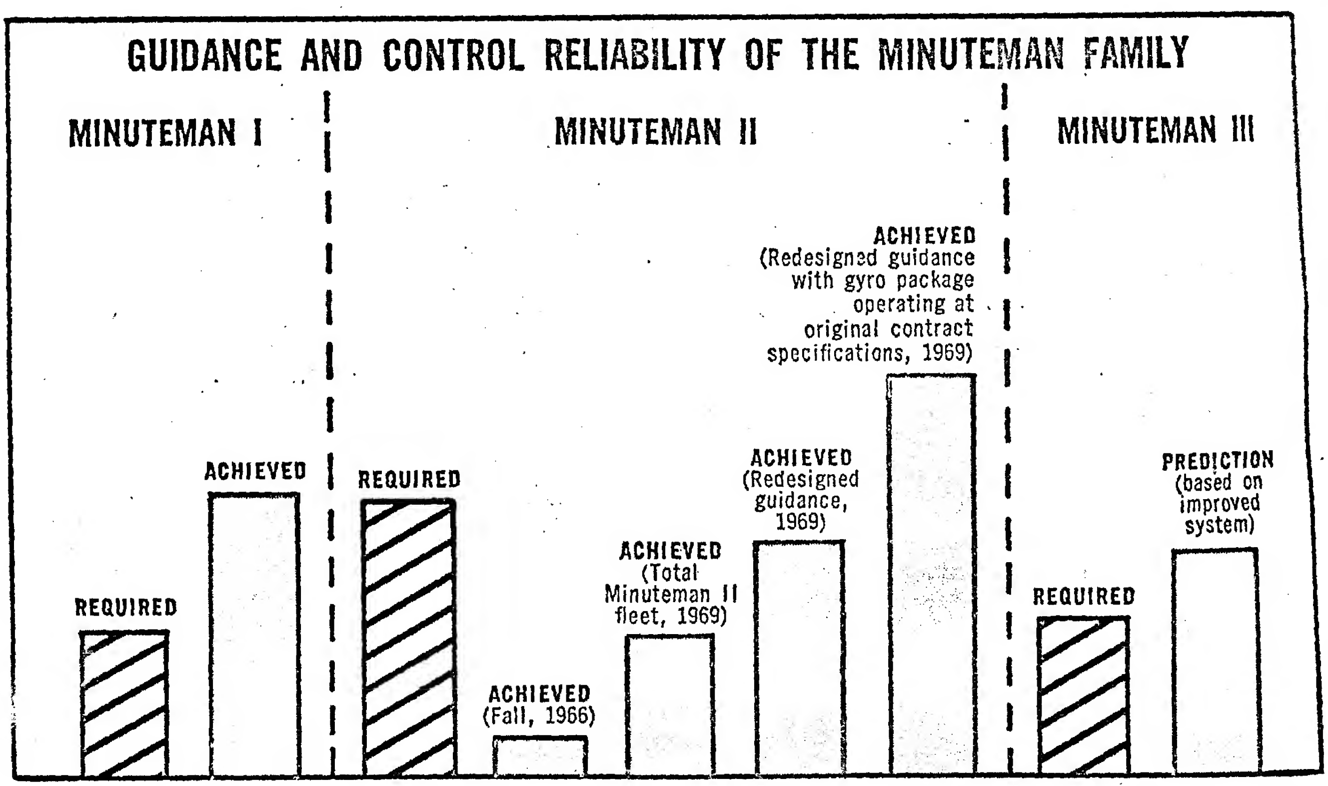
Technical literature from the electronics industry leaves no doubt about present trends. All major companies have built circuit components that are considerably advanced over those of the Minuteman II. These are in the fourth generation, or large-scale integration, listed on page 30, ranging up to 1,000 gates (elements for performing logical functions), with each gate containing several equivalent electronic parts on each chip. The main question today concerns the timing for marketing the new devices and for putting them to use on extremely sophisticated problems.

T. A. Smith, an RCA vice president, describes the problem in this way: "While the value of integrated circuits for military applications and for computers has been so great as to result in forced-draft production and application—in a much shorter time than would normally occur—techniques for both production and application still are changing. Until there is a higher degree of stabilization, it is likely that most applications of integrated circuits will be substitutes for older device functions. . . . Yet this is not the end; full exploitation

The clincher on the validity of the com[illegible] comes from the commercial, not the military, market. Fourth-generation computer parts already [illegible] stock item and are being sold under major [illegible] contracts. One of the most significant, [illegible] million, involves Autonetics and Hayakawa [illegible] Japan. Autonetics is producing 50,000 large [illegible] integration, fourth-generation chips per month [illegible] Japanese firm and plans to increase the rate to [illegible].

Hayakawa's initial use of the LSI circuits [illegible] low-cost desk-top calculator shown on page 31 [illegible] three chips are needed in each one, and, according to one description, a bushel of the *third-generation* [illegible] grated semiconductor circuit (ISC) chips would be needed to do the same job, at a much greater cost and lower reliability.

In one sense this development is disturbing. It is the first time in many, many years that electronic components being mass-produced for the world market are more advanced than those in US military systems. Then again this may be a very healthy sign. Commercial demand for advanced electronic systems may become so great that the military services will be relieved of some of the heavy research and development burden that they have borne so long. If the military can buy advanced technology off the shelf, with development costs borne by commercial product lines, the taxpayer will get a good deal more for his money.—END



Comparison of guidance and control reliability (mean time between failures) for the three Minuteman models is shown in the bar chart above. The scale showing the number of in-silo running hours between failures has been deleted for security reasons. However, it does illustrate the serious problem that the Minuteman II system has weathered.

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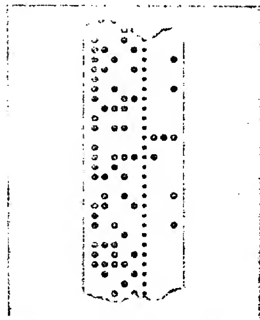

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